REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
13-10-2014	Conference Proceeding	-

4. TITLE AND SUBTITLE
Defect-related dark currents in III-V MWIR nBn detectors

5a. CONTRACT NUMBER
W911NF-11-1-0378

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
60124-EL.6

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
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15. SUBJECT TERMS
infrared detectors, MWIR, nBn, photodiode, defects, irradiation, lattice mismatch, dark current.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Gary Wicks
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					585-275-4867

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

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Conference Name: SPIE Defense + Security

Conference Date: May 06, 2014

Defect related dark currents in III-V MWIR nBn detectors

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ABSTRACT

The effect of defects on the dark current characteristics of MWIR, III-V nBn detectors has been studied. Two different types of defects are compared, those produced by lattice mismatch and by proton irradiation. It is shown that the introduction of defects always elevates dark currents; however the effect on dark current is different for nBn detectors and conventional photodiodes. The dark currents of nBn detectors are found to be more tolerant of defects compared to pn-junction based devices. Defects more weakly increase dark currents, and cooling reduces the defect-produced dark currents more rapidly in nBn detectors than in conventional photodiodes.

Keywords: infrared detectors, MWIR, nBn, photodiode, defects, irradiation, lattice mismatch, dark current.

1. INTRODUCTION

1.1 Barrier Architecture Detectors

The recent introduction of barrier architecture detectors has created the potential for improved performance for MWIR detection, particularly in the III-V material family[1]. This new class of detector has already shown significant advantages over conventional device architectures, like the pn junction based photodiode, due to their ability to naturally suppress many dark current mechanisms. Barrier architecture detectors have successfully shown suppression of surface leakage currents, depletion layer generation-recombination currents, trap-assisted tunneling, and direct band-to-band tunneling currents[2,3]. Furthermore, these devices have shown performance near Rule 07, indicating nearly Auger limited performance comparable to state-of-the-art HgCdTe MWIR detectors[4].

1.2 Defect-Dominated Dark Currents

In some applications for MWIR detectors, detectors may become limited by defect-related dark currents. The addition of defect states to the crystal structure of semiconductor-based detectors tends to increase the dark current of these devices. Significantly increasing the defect concentration can cause a measurable reduction in device performance[5]. Examples of cases where defect processes may dominate the dark current include grown-in defects such as in superlattice-based detectors; growth on mismatched substrates; and cases where devices will be subjected to the effects of a radiation filled environment. In such cases, using the detector architecture that minimizes the effects of the induced defects is an important consideration. The present work demonstrates that barrier architecture detectors have significant advantages over conventional pn photodiodes in these cases.

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Infrared Technology and Applications XL, edited by Bjørn F. Andresen, Gabor F. Fulop,
Charles M. Hanson, Paul R. Norton, Proc. of SPIE Vol. 9070, 907011 · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2050535

2. GENERATION – RECOMBINATION CURRENTS IN PHOTODETECTORS

2.1 Depletion Region Generation – Recombination Current

Shockley-Read-Hall (SRH) theory for generation and recombination in pn junction depletion regions describes the effect of defects on dark current density[6,7]. The theory predicts that the main effects of temperature and defect concentration are given by:

$$J_{Depletion} = Ce^{-E_g/2kT} N_{defect} \tag{1}$$

For depletion layer limited generation, SRH theory indicates a thermal activation energy of half the bandgap, and a direct proportionality between dark current density and defect density.

2.2 Neutral Region Generation – Recombination Current

Shockley's original theory also describes generation processes in neutral regions of semiconductors[6,7]. This process has a smaller magnitude effect than depletion region generation, and thus has traditionally been less important, at least in pn junctions. Defect-related generation in neutral regions has different dependences on defect density and temperature than generation in depletion regions. The main effects in the neutral region are given by:

$$J_{Neutral} = Ce^{-E_g/kT} \sqrt{N_{defect}} \tag{2}$$

In the neutral region case, the dark current density due to defects maintains a full bandgap thermal activation energy, and is proportional to the square root of the defect density. Although neutral region defects will increase the dark current density, the effect is smaller than that of depletion region defects.

2.3 Generation – Recombination Currents in nBn Photodetectors and Conventional Photodiodes

In conventional pn junction based photodiodes, generation in both the neutral region and the depletion region may occur; however, depletion region generation is usually dominant, thus defect-related dark currents in pn photodiodes are approximately equal to the dark current generated in the depletion region as indicated in equation 1. nBn detectors, ideally, do not have depletion regions. When nBn detectors are defect-dominated, only neutral region generation currents are possible, therefore, dark current density for defect-dominated nBn's follows equation 2.

The differing generation currents that dominate defect-limited pn junction photodiodes and nBn detectors results in two practical effects. Defect related dark currents in nBn detectors show a reduced dependence on the defect density when compared to photodiodes, and cooling is more efficient in reducing nBn's dark current due to the full bandgap activation energy.

3. PERFORMANCE OF InAs PHOTODIODES AND nBn DETECTORS

InAs pn junction photodiodes were grown via molecular beam epitaxy (MBE) on both lattice matched and lattice mismatched substrates. Lattice mismatched samples were grown on both InP and GaAs substrates. The InAs buffer thickness on mismatched substrates was varied. Other studies have shown that the defect concentration due to the lattice-mismatch scales inversely with the buffer layer thickness[8]. Dark current is plotted against the inverse of the buffer thickness in figure 1.

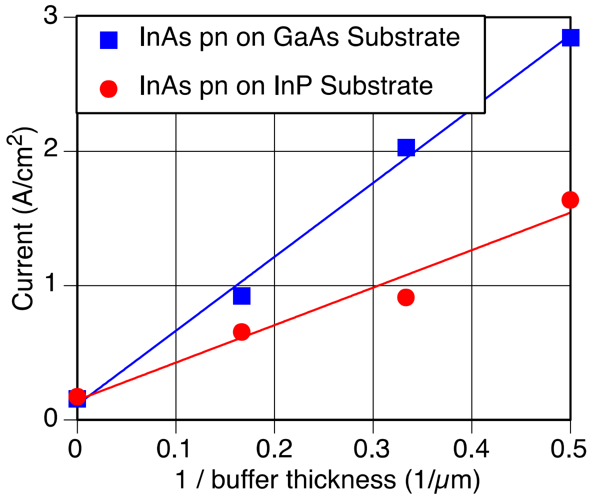

Figure 1. Current density vs. reciprocal buffer thickness for lattice mismatched InAs pn junction photodiodes on GaAs and InP substrates. Reciprocal buffer thickness is directly proportional to the density of defects that are associated with the lattice mismatch. Dark current density is shown to be well fit by a direct proportionality to the defect density.

The y-intercept point, indicated at zero reciprocal buffer thickness, or infinite buffer thickness, represent devices on lattice matched, InAs substrates. Since reciprocal buffer thickness is directly proportional to the defect density, fig. 1 shows that the dark current in mismatched pn photodiodes is directly proportional to the defect density, in agreement with equation 1. The lattice mismatch between InAs and GaAs is approximately twice that of the mismatch between InAs and InP, which causes the increased slope and thus elevated dark currents of the InAs photodiodes on GaAs substrates. The y-intercept value indicates the natural dark current present in the InAs detectors due to normal lattice-matched crystal growth and related dark current mechanisms. The horizontal axis indicates only the defects induced by the lattice mismatch.

Superlattice, MWIR nBn detectors were grown and irradiated with 63 MeV protons at low temperatures. The square of the dark current is plotted against proton fluence in figure 2.

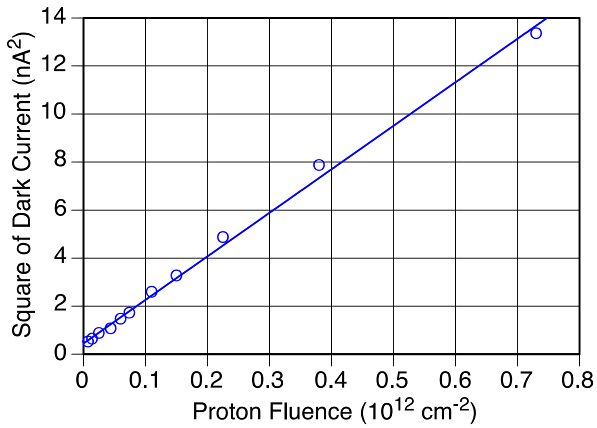

Figure 2. Square of the dark current as a function of proton fluence for proton irradiated MWIR nBn photodetectors. The square of the dark current is directly proportional to the proton fluence and the proton fluence is directly proportional to the defect density. The dark current in nBn detectors is proportional to the square root of the defect density.

There is a linear relationship between the square of the dark current and the proton fluence. Assuming that the density of irradiation-produced defects is proportional to the fluence, fig.2 indicates that the defect-related dark current in nBn detectors is proportional to the square root of the defect density, in agreement with equation 2. Since defect-related dark currents in conventional pn junction based photodiodes are directly proportional to the defect density, nBn detectors show an increased tolerance to defects by comparison. As in the case of the lattice-mismatched photodiodes, the y-intercept value is indicative of the natural dark current of the devices, present without the introduction of defects due to proton irradiation. The horizontal axis represents only the defects induced via proton irradiation at operating temperatures.

The temperature dependences of dark currents of both pn junction and nBn device architectures has also been studied. Figure 3 shows an Arrhenius graph of dark current density of conventional InAs photodiodes, grown both on a lattice matched, InAs substrate, and a lattice mismatched, GaAs substrate.

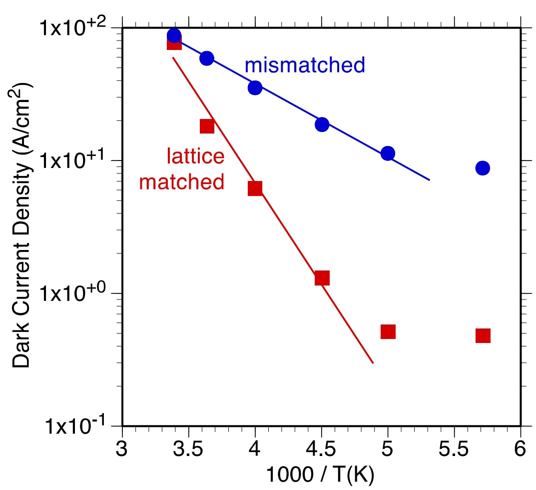

Figure 3. Dark current versus reciprocal temperature for lattice matched and lattice mismatched (GaAs substrate) InAs pn photodiodes. The thermal activation energy of lattice matched InAs photodiodes is equal to the bandgap of InAs (~0.31eV) down to ~210K at which point devices become surface leakage limited. Mismatched photodiodes on GaAs substrates exhibit activation energies slightly less than one half of the bandgap (~0.11eV) indicating behavior dominated by SRH generation in the depletion region.

Lattice matched, conventional InAs photodiodes show full bandgap activation energy, ~0.31 eV, from 300K to about 210K. Below this point, the dark current density becomes temperature independent, indicating the onset of surface leakage limited performance. The lattice mismatched InAs photodiode on a GaAs substrate shows an activation energy of ~0.11 eV, showing elevated dark currents on account of the increase in defects as well as a reduced rate of reduction in dark current density under cooling.

Dark current density as a function of temperature has also been studied for InAs nBn detectors on both InAs substrates and lattice mismatched GaAs substrates (figure 4).

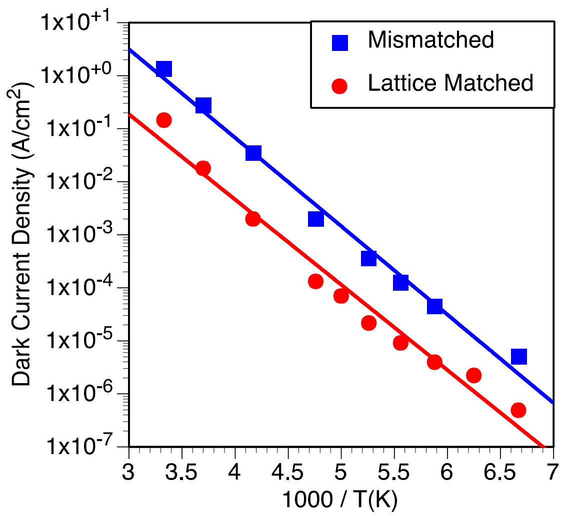

Figure 4. Dark current versus reciprocal temperature for lattice matched and lattice mismatched (GaAs substrate) InAs nBn detectors. The thermal activation energy (~0.35eV) is equal to the bandgap of InAs over the entire temperature range for both lattice matched and mismatched devices. Mismatched nBn detectors exhibit increased dark current densities compared to lattice matched nBn detectors.

The InAs nBn detectors on GaAs substrates show about an order of magnitude more dark current than comparable lattice matched InAs nBn's, indicating that inducing defects increases dark current levels in nBn detectors; however, the lattice mismatched nBn maintains a full bandgap activation energy, ~0.35 eV, equal to that of the lattice matched nBn across the entire measureable temperature range. This is a significant advantage that nBn detectors hold over conventional pn photodiodes. Although defect-limited nBn detectors and conventional photodiodes both show elevated dark currents compared to low defect concentration devices, the nBn maintains its full bandgap activation. This means defect-limited nBn detectors respond better to cooling than comparable pn junction based devices where depletion layer generation currents limit the defect-related activation energy to one half of the bandgap.

4. CONCLUSIONS

Defects elevate dark currents in both nBn detectors and conventional pn junction photodiodes; however, in cases where the defects limit dark currents, barrier architecture detectors offer significant benefits over pn photodiodes. nBn detectors are naturally more tolerant to increases in defect concentration, and defect-related dark currents reduce more quickly in nBn detectors under cooling. As a result, nBn detectors may be operated at a higher temperature than pn junction photodiodes in the presence of high defect levels. Defect-limited InAs nBn's show about four orders of magnitude less dark current, compared to conventional photodiodes at an operating temperature of 200K.

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